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Biosystems for Air Protection

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1. Introduction

With rapid development of industry and technology worldwide we are observing a gradual deterioration of the air quality. A great number of industrial processes (e.g. combustion), transportation, or even agriculture generate significant quantities of pollutants such as carbon dioxide, carbon monoxide, sulphur oxides, nitrogen oxides, volatile organic compounds (e.g. methane), ammonia, particulate matter, toxic metals (e.g. lead), odors and radioactive pollutants. These pollutants have a harmful effect on the ecosystems, human and animal health. In order to prevent from further deterioration of air there is a need for minimizing the emissions of harmful substances, performing pollution control and introducing solutions to reduce the concentrations of pollutants in the air.

Living organisms – referred to as biosystems – such as microorganisms, plants or animals in their natural habitat can respond to some changes in the air quality. Living organisms can respond to air pollutants in many ways which include e.g. accumulation of a pollutant in a tissue, visual changes on the community level, tissue injury, inhibition of growth, etc. These effects of pollutants on living organisms can be measured qualitatively and/or quantitatively. Organisms also use selected air pollutants for their growth and metabolism. Some of them have the ability to accumulate various substances and transform into less toxic. This can result in a significant decrease in the concentration of these pollutants in the air. Due to these specific properties biosystems can be used in monitoring of pollutants in the air referred to as biomonitoring. They can also allow for the reduction and removal of toxic compounds present in the air.

This chapter will provide the overview of the most common biosystems that can be used in the protection of air with the examples of practical applications, current trends and recent developments. The main focused will be place on the characteristics of biosystems and their potentials and limitations for air protection, mechanisms and processes for accumulation and transformation of air pollutants, biomonitoring for air pollution control, and mechanisms for reduction and removal of pollutants from the air. This chapter will also present current research and future challenges in the application of biosystems for air protection.

2. Air pollution and quality control

2.1 Air pollutants

Air pollutants are referred to as gaseous, liquid and solid substances present in the atmosphere which are not the natural components of the air or any substances which are present in the atmosphere exceeding the concentrations of the air components typical for the natural composition of the air. The sources of air pollutants are natural (e.g. volcano eruptions, forest fires, pollens scattering, etc.) and anthropogenic (i.e. industrial processes, such as combustion, power generation, services also transportation, residential sources, and agriculture). Air pollutants are emitted to the atmosphere mainly from industrial processes, transportation or agriculture, and they constitute a very diverse group of substances. Generally, they are classified as primary and secondary air pollutants. The primary air pollutants are directly emitted from the source to the atmosphere (e.g. carbon dioxide, sulphur dioxide, hydrocarbons, etc.) whereas the secondary air pollutants are formed in the atmosphere due to various reactions and transformations (e.g. aerosols, nitrogen dioxide or tropospheric ozone, etc.). With view to the physical state the air pollutants can be gaseous, liquid or solid. Gaseous air pollutants include sulphur dioxide, nitrogen oxides, carbon oxide, volatile organic compounds, toxic organic compounds (polychlorinated biphenyls, polycyclic aromatic hydrocarbons, dioxins), greenhouse gases (carbon dioxide, methane), odors. Liquid substances and solid particles are also emitted to the atmosphere where they form aerosols and suspended particulate matter.

The most hazardous air pollutants include: carbon dioxide, carbon monoxide, sulphur oxides, nitrogen oxides, volatile organic compounds (e.g. methane), ammonia, particulate matter, toxic metals (e.g. lead), odors and radioactive pollutants. Sulphur dioxide is mainly produced from the combustion of sulphur-containing fossil fuels and in the atmosphere it can be oxidized to sulphurous and sulphuric acids. Also some sulphur generate from petroleum refining, production of sulphuric acid and paper (Vestreng et al., 2007). Carbon dioxide and methane are the greenhouse gases that contribute to the global warming. Carbon dioxide is generated during combustion of fossil fuels, i.e. oil, natural gas and goal, biomass and various solid waste, and also is produced from industrial processes. Methane is formed and emitted to the atmosphere from the production and transport of fossil fuels, from agriculture and landfilling of waste. Another important air pollutant on the regional as well as global scale is tropospheric ozone (Klumpp et al., 2006) which can have both a direct and indirect effect on the global warming. It is generated during photochemical reactions of NO_x and VOCs and its formation is influenced by any pollutants produced during fuel combustion. Nitrogen oxides are emitted to the atmosphere mainly from the combustion of fossil fuels (e.g. during power generation) and from transportation. Particulate matter suspended in the air is defined as a heterogeneous mixture of solid and/or liquid particles of different sizes, origin and chemical composition (Grantz et al., 2003). These particles can be generated during combustion of e.g. diesel fuel or due to churning of road dust, brake wear and also construction and agricultural activities. For the purpose of air monitoring there are two sizes of particles referred to as particulate matter with the particle size smaller than 10 μm (PM 10) and 2,5 μm (PM 2,5). Other air pollutants include heavy metals and fluoride. Heavy metals such as Cd, Cr, Co, Cu, Mn, Ni, Pb are emitted to the atmosphere from a large number of industrial processes. Fluoride is a bioelement which shows a very narrow safety margin for the environment, and therefore can pose a significant threat

towards living organisms. The main source of this air pollutant is the application of fluoro-pesticides which can enter the food chain. In the environment fluoride can form various compounds such as gaseous HF and SiF_4 which are toxic and can easily penetrate into living organisms, soluble in water salt derivates and other fluoride compounds which are partly soluble in water (Telesiński & Śnioszek, 2009).

Not only atmospheric air is polluted with various chemical compounds. Also, the indoor air in non residential buildings (i.e. workplaces, offices, production facilities, warehouses, etc.) can be polluted with a number of substances, such as aromatic hydrocarbons (e.g. benzene, toluene, etylobenzene, isomeric xylens, etc.), chlorine, ozone, formaldehyde, sulphur dioxide, nitrogen dioxide and other (Ilgen et al., 2001). Generally, these indoor air pollutants are emitted from combustion processes, furniture, cleaning agents and human activity. According to the EPA about 1000 sources of indoor pollution have been identified and over 60 of them emit carcinogenic substances. In the case of indoor air pollution the most effective methods for removal or/and reduction of air pollutants are eliminating the source of indoor air pollutant emission and/or reducing the concentration of indoor air pollutant by ventilation.

Apart from already known pollutants emitted to the atmosphere there is a large and unspecified group of so called emerging pollutants. These are substances used in many areas of life, such as surfactants, pharmaceuticals, gasoline additives, steroids, hormones, etc. The effects of emerging pollutants on living organisms continuously released to air, water and soil have not been yet sufficiently investigated and thus the future consequences are difficult to predict (Rodrigues-Mozaz et al., 2005).

Air pollution causes potential threats and risk to people, animals and natural environment. The direct effects of air pollution include pulmonary deposition and absorption of inhaled chemical compounds which are hazardous to human health. The indirect effects can result from the exposure and/or uptake of food and drinking water which can contain air pollutants deposited in the environmental media (Van Leeuwen, 2002). Heavy metals can cause neurological problems and cancer in humans. According to the EEA (i.e. European Environmental Agency) in European cities during the period of 1997-2007 about 20-50% of people were exposed to particulate matter (PM10) concentration which exceeded the admissible values. During that time about 13-41% of urban population was exposed to nitrogen dioxide concentrations which also exceeded the admissible values. As for ozone it is estimated that about 14-62% Europeans in cities were exposed to the ozone concentrations which were higher than the admissible values. The urban population exposed to sulphur dioxide in European counties decreased to less than 1%. According to recent studies the exposure to airborne particulate matter and ozone may have increased the mortality rate and admissions to hospitals due to respiratory disorders, cardiovascular diseases and lung cancer (Brunekreef & Holgate, 2002). Fluoride impairs the assimilation and photosynthesis in plants. Also, particulate matter has the negative effects on plants and ecosystems which are mostly due to deposition resulting in impairing nutrient cycle, vegetation growth and ecosystem functions. Some direct effects include injury of leaf surfaces by pH (Grantz et al., 2003).

2.1 Control of air quality and pollution

The quality and pollution of air are controlled by continuous monitoring of atmosphere. Monitoring is a system of measuring and analyzing the parameters of air quality, and collecting, processing and publicizing the obtained data from the observation networks (e.g. automatic, manual, passive measurements.). Monitoring of air is performed on a local, regional, national and global scale. In most countries monitoring of air quality and pollution is performed through various regulatory incorporating and control-oriented programs and strategies. These programs are developed in order to provide reliable data on the occurrence and concentrations of the selected pollutants in the atmosphere. In practice, monitoring of air control and pollution requires identifying the sources of emissions, determining the scale of emissions, adapting analytical methods, determining critical emissions and evaluating the total costs. Monitoring of atmosphere poses many difficulties. Mostly, this is due to the dynamics of atmosphere which is the main medium for spreading and transporting the pollutants between different elements of the environment (i.e. air, water and soil) and the exposure of large human populations to the harmful and/or toxic air pollutants.

Monitoring of air aims at: controlling of air quality according the required standards, identifying and determining the sources and scale of emissions, determining the effects of air pollution on the environment, analyzing the processes which occur in the atmosphere. Depending on the aim, localization and scale, the quality and pollution of air is determined from the presence and concentration of the selected parameters. The essential parameters of air pollution are SO_2, NO_2, NO_x, PM 10, PM 2,5, Pb, CO, C_6H_6, O_3 and also As, Cd, Ni in PM 10.

Monitoring of air pollution is conducted on a local, regional, national and international levels and the data on the concentration of the air pollutants is available through websites of different agencies or governmental organizations on regular basis (for Europe it is the European Environment Agency). According to recent data on the pollution of air presented by the EEA, there is a strong declining trend for the emissions of nitrogen oxides which decreased by 31% from 1990 to 2007. It is estimated that the emissions of NO_x mostly came from road transport (36%), combustion for energy production (21%), use of energy for industrial purposes (15%) and other non road transport sources (16%). In the European countries the emissions of heavy metals during 1990 and 2007 also decreased. The emissions of lead, mercury and cadmium were reduced by 88%, 57% and 56%, respectively. During the last 25 years anthropogenic sulphur emissions in Europe show a steadily decreasing tendency. According to the reports from the Cooperative Programme for Monitoring and Evaluation of the Longrange Transmission of Air Pollutants in Europe (EMEP) the emissions of sulphur dioxide were reduced from 55 Tg SO_2 in 1980 to 15 Tg in 2004. Most European countries have reduced the emission by 60% during the period of 1990 and 2004 with the highest reductions in the sulphur emissions from combustion for energy and also transformation industries (Vestreng et al., 2007).

3. Biological indicators of air pollution

It has been known for a long time that many living organisms such plants, animals, fungi and bacteria are sensitive to many pollutants present in the air, soil and water. These living organisms can respond to different types of substances and the concentration. Therefore

they can be used as valuable tool for identification of the impact the air pollutants have on the natural environment. The application of living organisms for identifying and determining the impact of air pollutants on the environment requires the knowledge about the cause and effect and the exposure and response relationships. These relationships have to be defined in terms of qualitative and quantitative changes caused by a selected air pollutant to a living organism. Based on that several methods and organisms which demonstrate the ability to respond with specific and visible symptoms to air pollutants have been identified. These include:

- bioindicators (or bioindicator organisms) are organisms or a group of organisms that contain information on the quality of the environment (Markert, 2008) and refer to changes which can mainly occur at the organismic and population level (Lam & Gray, 2003),

- biomonitors are organisms that contain information on the quantitative aspects of the quality of the environment,

- bioaccumulators are organisms which demonstrate the ability to accumulate a substance or group of substances in their tissues; bioaccumulation can result from the equilibrium process of intaking/discharging a pollutant by biota from and into the surrounding environment (Batzias & Siontorou, 2007),

- biomarkers are often defined as quantitatively measurable changes in living organisms at the cellular, biochemical, molecular or physiological levels, i.e. measured in cells, body fluids, tissues or organs which were exposed to the action of pollutants; the examples of biomarkers include tanning of human skin as an effect of UV radiation, changes in morphological or histological structure of organs, such as liver or testicles (Lam & Gray, 2003; Markert, 2008); in the studies on the risk of lung cancer due to air pollution molecular alterations such as loss of heterozygosity or gene mutations are investigated as potential biomarkers (Vineis & Husgafvel-Pursiainen, 2005),

- biosensors are referred to as measuring devices which generate a response corresponding to the concentration of a selected substance or a defined group of substances through a selective biological system such as enzyme, antibody, membrane, cell or tissue to a physical transmission device (Markert, 2008); in other words, biosensors combine a response to the concentration of a selected pollutant with a measurable signal (e.g. microbial fuel cells biosensors can use microorganisms which in a response to the presence and/or concentration of given pollutant can generate electricity); these biosensors can detect a substance or a group of substances or can give information on biological effects (e.g. genotoxiicty or immunotoxicity) (Batzias & Siontorou, 2007).

In terms of applied methods, biological organisms can be also classified into active and passive organisms. Active organisms are grown in laboratories and transferred into the environment whereas passive organisms (also referred to as native or in situ organisms) are already present in the environment. In terms of bioindication both types of organisms have advantages as well as some limitations. Active organisms which are transplanted into the designated area can only show accumulation of air pollutants during the selected period of study and the concentration of air pollutants may not be detectable with the commonly applied methods (Markert, 2008). Organisms transplanted into the area subjected to monitoring allow to control the range and the density of observation network.

For the purpose of biomonitoring living organisms with the potential for bioindication and bioaccumulation should also fulfill a number of requirements. They should be easily recognized and sampled, and respond quickly to changes in the environment. The cause-effect or exposure-response relationships between a pollutant sensitive organism and a pollutant itself should be clearly determined. The selected organisms should commonly occur in the area subjected to monitoring, their living requirements should not be too limited and allow for automatic and continuous monitoring of their responses. Further selection of biological indicators can be performed in view to specificity, accumulative properties and representation of a monitored site (Wolterbeek, 2002). Also, the sampling design for a monitored site should allow for statistically reliable results that can be comparable (Lam & Gray, 2003). McGeoh and Chown (1998) determined the value of species as indicators of air pollution based on the specificity and fidelity measure. This method allows to identify and determine biological indicators for a selected area or habitat types subjected to monitoring.

4. Biomonitoring of air pollution

In recent decades the increased interest in the application of biological indicators for monitoring of air pollutants is observed worldwide. Biomonitoring can be defined as the use of living organisms and/or biological materials to provide some information on a selected parameters and characteristics of the environment. It is a direct measure of a living organism's exposure to a pollutant or a group of pollutants. Biomonitoring uses sensitive or bioaccumulative organisms. This refers to the changes in the behavior of living organisms or the concentration of a pollutant in tissues (Wolterbeek, 2002; Batzias & Siontorou, 2007).

In many countries biomonitoring is strongly affected by the environmental policies, regulations and international agreements. Each country can develop and implement its own policies and programs for biomonitoring of air pollution. This however results in inconsistent programs, procedures and methodologies. Due to the fact that biomonitoring can be applied at local, regional, national or global scale, it requires further development and unification to allow for obtaining comparable and reliable results for larger geographical scales (Pirintsos & Loppi, 2008).

There are many advantages of applying biological indicators for monitoring the quality and pollution of air. One of the advantages of biomonitoring is that it provides an early warning of future effects which air pollutants can have on biosystems. Chemical analytical methods applied in monitoring do not allow for determining the direct impact of air pollution on living organisms (Lam & Gray, 2003). The application of biological indicators for monitoring of air pollution is also cost-efficient when compared to the cost of analytical methods. Possible limitations of biomonitoring may be due to the selection of a biological indicator, unpredicted changes in the environment which can affect the cause-effect relationship and make it difficult to determine the impact of a pollutant, sampling methods and also the area subjected to monitoring. The optimal solution for monitoring of air quality and pollution is the application of living organisms coupled with monitoring performed with chemical analytical methods.

The first observations of a response of living organisms to air pollutants were: the abundance of lichens and the acidification of Scandinavian lakes due to sulphur emissions in Europe (Wolterbeek, 2002). Currently, there are many species that are used for biomonitoring of various air pollutants.

Gaseous pollutants in the atmosphere such as SO_2, NO_2, HF or O_3 were initially monitored with the use of lichens which have been regarded are the long-term biomonitors of air pollution (Batzias & Siontorou, 2007). At present, many researchers investigate other plant species for biomonitoring gaseous pollutants, e.g. wheat, barley, maize, grass and tobacco (Wolterbeek, 2002). Klumpp et al. (2006) conducted research on monitoring of tropospheric ozone present in the atmosphere with the use of tobacco plant (*Nicotiana tabacum* cv. Bel-W3). The study was conducted in urban, suburban, rural and traffic exposed areas. Kumpp et al. observed the ozone-induce injury of tobacco plant mostly in suburban and rural areas. Pacheco et al. (2002) investigated olive-tree bark (*Olea eurpaea*) as a biological indicator for airborne trace elements. Olive-tree bark can be sampled and analyzed in a similar manner as lichens.

Biomonitoring of air polluted with heavy metals can be performed with the application of mosses. Mosses show high capacity for bioaccumulation of heavy metals due to their ability to retain particulate matter on the surface of the plant or absorb heavy metals in ionic forms (Shakya et al., 2004). Costa at al. (2002) investigated lichens as biomontiors for heavy metals in air particulate matter. However they found it difficult to establish quantitative relationship between lichens and particulate matter.

The pollution of fluoride can be monitored by various biosystems mostly plants. Plats can be affected by fluoride present in particulate matter or industrial gasses, or by direct intake of fluoride present in soil by root system. Fluoride air pollution can be monitored by gladiolous flowers which show a direct correlation between the size of necrosis of the leaves and the concentration of fluoride in the air or waste. Other bioindicators include tulips, crocuses, pines, larches, lichens and also mosses. Biomonitoring of fluoride air pollution by plants and soil organisms allow to determine the effect of fluoride on a living organism for a selected period of time (Telesiński & Śnioszek, 2009).

5. Removal of air pollutants with biosystems

Currently, the effect of climate change is the most challenging and globally recognized threat caused by increasing emissions of greenhouse gases, predominantly by CO_2 (Woodward et al., 2009), and other pollutants that are emitted to the atmosphere.

Strategies for removal and/or mitigation the effects of air pollutants include: replacing fossil fuels with renewable sources of energy such as wind, solar, geothermal or nuclear energy; injecting carbon dioxide into the oceans or employing biological systems for removal of air pollutants or mitigate the effects of air pollution. Woodward et al. (2009) presented a number of biological methods for reducing carbon dioxide in the atmosphere. These methods included: reducing carbon dioxide through soil carbon sequestration based on the management of plant and decomposition processes, reducing carbon dioxide concentrations

by afforestation, reducing surface warming by increasing the albedo of crop leaves, and remediation of anthropogenic carbon dioxide by ocean biota.

Reduction in the concentration of air pollutants by various organisms strongly depends on their ability to take up selected compounds. The mechanisms for taking up selected pollutants by living organisms include: bioaccumulation which depends on the ability to store different compounds by living organisms, biomagnification which is referred to as absorption of different pollutants from nutrients through the intestines and is typical for heterotrophic organisms, and bioconcentration is a direct uptake of pollutants from the environment through tissues and organs, and is typical for plants and aquatic animals (Markert, 2008).

Reduction of air pollutants with various species is mostly based on photosynthesis. Photosynthesis is the process in green plants, algae and certain forms of bacteria by which carbohydrates are synthesized from carbon dioxide and water in the presence of chlorophyll, using light as an energy source, and releasing excess oxygen as a byproduct. Photosynthesis consists of light reactions and dark reactions. This process can be simplified in this equation:

$$6CO_2 + 12H_2O + energy \rightarrow C_6H_{12}O_6 + 6O_2 + 6H_2O \qquad (1)$$

Approximately 40% of the overall amount of carbon annually fixed on the Earth is occurring in the oceans in the process of photosynthesis by photoautotrophic organisms. Photoautotrophic organisms are able to synthesized their own food without rely on nutrients derived from other living organisms. Within the cells of plants and algae photosynthesis occurs in plastids (e.g. chloroplasts), which are membrane-bounded organelles containing photosynthetic pigments (e.g. chlorophyll). On the contrary to the photosynthetic bacteria (cyanobacteria) that do not have membrane-bounded organelles. In those organisms the process of photosynthesis occurs in the thylakoid membranes in the cytoplasm.

Currently, due to the effects of greenhouse emissions there is a tremendous interest in combining systems of reducing/mitigating the concentration/effect of greenhouse gases with biomass production for material and energy recovery. Therefore there is an increasing interest in applying algae for removal of air pollutants (mostly CO_2, NO_2, SO_2).

6. Algae potential for removal of air pollutants

Photoautrophic organisms like algae can absorb some of the air pollutants. Algae produce over 71% of the earth's oxygen in the process of photosynthesis. Algae belong to organisms which are able to absorb CO_2, NO_2, SO_2 that are important nutrients for them. Moreover, addition of CO_2 to algal cultures stimulates its growth. Algae can be either marine or freshwater. They have higher photosynthetic efficiencies than terrestrial plants and therefore they are more efficient capturing carbon. Algae include seaweeds and microalgae. Seaweeds are macroscopic multicellular algae that have defined tissues containing specialised cells. Microalgae are microscopic algae, many are unicellular (Packer, 2009).

Fuel source and design of the plant is responsible for the level of concentration of the CO_2 in flue gases. Generally, coal-fired plants having higher CO_2 emissions. Other constituents of the flue gases can be: oxides of nitrogen (NOx) and sulphur (SOx) and metals, such as: nickel (Ni), vanadium (V) and mercury (Hg) (Packer, 2009). Carbon dioxide and nitrogen dioxide are also released by automobiles, steel plants, cement plants, breweries and fertilizer plants. Current research indicates that algae have the potential to be able to accumulate trace metals released to the environment by biosorption and bioaccumulation processes. Wastewater could be used as microalgae nutrient and algal biomass could become, in the near future, an economic and effective material for selective recovery of heavy metals from communal and industrial wastewater or other sources (Munoz et al., 2009).

According to the literature, microalgae growth is not inhibited in a medium containing NO_x. The concentration of SO_x above 400 ppm resulted in the formation of sulphurous acids and impact the pH. Then, the pH of the medium can become lower than 4 that affects the productivity of the microalgae. For inhibition of fast increase of pH value it is possible to use NaOH.

Microalgae present one of the technologies for the capture of carbon dioxide emitted by industrial sources like fossil-fuelled power plants and fermentation processes, reducing CO_2 emissions (Usui & Ikenouchi, 1997; Benneman, 1997; Braun, 1996). Microalgae can assimilate carbon dioxide into organic material: carbohydrates, proteis and lipids that can be converted into valuable materials. One of the most important applications of algal biomass is that it can be used for production of different types of renewable biofuels, such as (Chisti, 2007): methane produced by anaerobic digestion of the algal biomass, biodiesel derived from microalgal oil, bioethanol derived from microalgal carbohydrates, photobiologically produced biohydrogen.

The algal biomass could also find application as: high-protein animal feed, food, agricultural protein-rich biofertilizer, biopolymers/bioplastics, biosorbents, medicines, cosmetics.

Optimal temperature for growing many microalgae is between 20 and 30°C and their tolerance to CO_2 depends on the species. For the chlorophylls and other photosynthetically active pigments the spectral quality of light is defined by absorption spectrum in the range of 400 to 700 nm.

6.1 Algae cultivation systems

Generally, there are two types of cultivation systems of algae: open ponds and by using enclosed photobioreactors. Photobioreactors design in a variety of configurations are currently used for algae cultivation. With reference to the investigations on CO_2, many researchers observed that photobioreactors have been successfully used for producing large quantities of microalgal biomass (Molina Grima et al., 1999; Huntley & Redalje, 2006; Frac et al., 2009). The most common photobioreactors are: flat plate, thin-panel or tubular.

The diffusion of CO_2 from the air into the water is 0.03% that is too low for rapidly growing algae. The dissolving rate of gaseous CO_2 depends on temperature, pressure, bubble size, the state of saturation of the medium for CO_2 and the mixing. The continuous mixing is also very important in order to enhance nutrient distribution, to eliminate thermal stratification, to keep cells in suspension and to enhance light utilization efficiency (Suh & Lee, 2003). All of these parameters are connected to the types of cultivation system.

Open ponds systems for cultivation of algae can be categorized into natural waters (lakes, lagoons, ponds) and artificial ponds or containers. One of the disadvantages is that algae in

open culture system could be contaminated by predators and other fast growing heterotrophs. A typical raceway open pond system for algae cultivation is made of a closed loop recirculation channel. Circulation is provided by a paddlewheel that operates all the time to prevent sedimentation. Tubular photobioreactors and solar collectors are used for microalgal culture. For example, a tubular photobioreactor consists of an array of tubes that are usually made of plastic or glass (Chisti, 2007).

The most important advantages of enclosed photobioreactors are overcoming the problems of contamination and evaporation encountered in open ponds. Furthermore, the biomass productivity of photobioreactors is more higher than that of open pond. Algal biomass is about 30 times as concentrated as the biomass found in open pond. As a result, the harvest of biomass from photobioreactors is less expensive. Environmental control of important physico-chemical parameters (temperature, pH, pCO_2, etc.), effective sterilization of the system and easier maintenance of a monoculture are improved (Suh & Lee, 2003). However, enclosed photobioreactors are difficult to scale up.

Jorquera et al. (2010) performed comparative analyses of the energy life-cycle for production of biomass from the oil-rich microalgae *Nannochloropsis sp.*, using raceway ponds, tubular and flat plate photobioreactors in order to evaluate their feasibility. The researchers found that the use of horizontal tubular photobioreactors is not economically feasible. Furthermore, they concluded that both flat plate and raceway photobioreactors are economically feasible for mass cultivation of *Nannochloropsis sp.*

The ability of microalgae to attach to photobioreactors' walls constitutes an operational problem. Munoz et al. (2009) evaluate the potential of flat plate and a tubular photobioreactor with a an algal-bacterial biofilm, using a *Chlorella sorokiniana-Ralstonia basilensis* consortium immobilized onto the reactor walls for the treatment of industrial wastewaters. According to these researchers, the biomass immobilization maintain a high microbial activity at all operating conditions, protecting cells from pollutant toxicity and producing an effluent containing easily settleable microbial flocks. However, such type of photobioreactors have limitations that could restrict their widespread application, such as: photoinhibition in outdoors cultures, because of immobilized microalgae are constantly exposed to a high photon flux density and there is a risk of clogging due to biomass overgrowth.

Merchuk & Wu (2003) reviewed the mathematical model of the process of photosynthetic growth that integrates algal growth kinetics and fluid dynamics of the bubble column photobioreactor. Simulations carried out with the model allowed, by extrapolation, qualitative prediction of the expected behaviour of photobioreactors, such as: optimal column diameter, as a function of illuminance and gas superficial velocity in the bubble column. It also describes the dependence of photoinhibition on cell density and actual biomass decrease.

Each system has its advantages and disadvantages. In order to choose the best system the following factors such as the production costs, type of the desired products and the production quantity of the products should be considered.

6.2 Removal of air pollutants by algae

Flue gases from power plants are responsible for more than 7% of the total world CO_2 emissions from energy use and industrial exhaust gases contains up to 15% CO_2 (Mata, 2010). Chemical reaction-based approaches and the biological mitigation are the most

common CO_2 mitigation strategies. The capture of carbon dioxide produced by combustion of fossil fuels by amine scrubbing of the flue gases may be replaced by options such as membrane separation, molecular sieves or desiccant adsorption. The disadvantages of chemical reaction-based approaches are: energy-consuming, use costly processes, and have disposal problems of the wasted adsorbents. Furthermore, sequestration by direct injection into geologic or oceanic sinks also do not address issues of sustainability (Stuart & Hessami, 2005).

Many researchers recommend that micro-organisms capable of photosynthetic reactions may hold the key to reducing emissions in both an economically and environmentally sustainable manner. Stuart & Hessami (2005) found that that a 4000 m^3 pond under natural daily light exposure cycles could sequester up to 2.2 ktonne of CO_2 per year.

Key advantages of the capture of CO_2 using algae are:

high purity CO_2 is not required for algae cultivation,

combustion products, such as: NO_x and SO_x can be used as nutrients,

the process has minimal negative impacts on the environment,

cultivation of algae provide high value commercial products.

Chiu et al.(2008) cultured the marine microalga *Chlorella sp.* in a photobioreactor to assess biomass, lipid productivity and carbon dioxide reduction. They also determined the effects of cell density and CO_2 concentration on the growth of *Chlorella sp.* The researchers indicated that at CO_2 concentrations of 2%, 5%, 10% and 15%, the rate of CO_2 reduction was 0.261, 0.316, 0.466 and 0.573 g h^{-1}, and efficiency of CO_2 removal was 58%, 27%, 20% and 16%, respectively. They concluded that efficiency of CO_2 removal was similar in the single photobioreactor and in the six-parallel photobioreactor. However, production of biomass, and production of lipid were six times greater in the six-parallel photobioreactor than those in the single photobioreactor. The researchers found that airstreams containing a high concentration of CO_2 (2–15%) may be introduced directly into a high-density culture of *Chlorella sp.* in a semicontinuous photobioreactor. The maximum efficiency of CO_2 reduction reached 58% in the culture aerated with 2% CO_2. The greatest mass of CO_2 that was reduced (17.2 g L^{-1} d^{-1}) occurred at 15% CO_2. The results obtained by the authors indicated that productivity and efficiency of CO_2 reduction did not decrease when a parallel (multiple units) photobioreactor was used.

Sung et al. (1999) determined the tolerance of *Chlorella sp.* KR-1 strain to high concentrations of CO_2. The investigators observed the maximum growth at 10% CO_2 and a good growth rate up to 50% CO_2. They indicated the feasibility of the KR-1 strain for mass cultivation using condensed stack gases.

Morais & Costa (2007) added CO_2 at different concentrations to cultures of the eukaryotic microalgae, *Chlorella kessleri, C. vulgaris* and *Scenedesmus obliquus*, and the prokaryotic cyanobacterium, *Spirulina sp.* The experiment was conducted in flasks and in a photobioreactor. The researchers found that the best kinetics and carbon fixation rate were with a vertical tubular photobioreactor. Overall, *Spirulina sp.* had the highest rates. *Spirulina sp., Sc. obliquus* and *C. vulgaris* could grow with up to 18% CO_2. The obtained results demonstrate that these three species could be used to mitigate the effects of CO_2 by reducing emissions of flue effluents.

Cheng et al. (2006) studied carbon dioxide removal from air by microalgae cultured in a membrane-photobioreactor. They found that the photosynthetic CO_2 fixation was strongly dependent on the concentration of CO_2 continously provided during the algal growth.

Furthermore, the researchers concluded that compared to that in the ordinary photobioreactor, the CO_2 fixation capacity in the membrane-photobioreactor was enhanced from 80 to 260 mg L^{-1} h^{-1}. However, membrane modules must resolve some problems with fouling and pressure resistance to make sure that high mass transfer rates are maintained for extended periods of operation.

Jacob-Lopes et al. (2008) studied the integral method for the analysis of kinetic data to describe the removal of carbon dioxide dissolved in the aqueous phase of a tubular photobioreactor by cyanobacteria *Aphanothece microscopica Nageli.* The effects of the carbon dioxide concentration (3, 15, 25, 50 and 62%), light intensity (960, 3000, 6000, 9000 and 11,000 lux) and temperature (21.5, 25, 30, 35 and 38.5^{0}C) were considered. The researchers indicated that sequestering CO2 by way of the formation of carbonates and bicarbonates is limited by the concentration of OH$^-$ ions present in the aqueous phase of the reactors, caused by the establishment of chemical equilibrium. In case of using microalgae, the alkaline environment is provided by the action of the microbial metabolism responsible for the transport of hydroxide ions to the outside of the cell using a reaction catalysed by the enzyme carbonic anhydrase, associated with the capture of H$^+$ ions for the interior of the thylakoid membranes, resulting in the production of highly alkaline environments with consequently very efficient CO_2 fixation capacity.

Jacob-Lopes et al. (2010) performed laboratory experiments to study the capacity of CO_2 sequestration and carbon fixation into biomass during the cultivation of the cyanobacteria *Aphanothece microscopica Nageli* in refinery wastewater. The influence of the photoperiod (day/night) on the rates of CO2 sequestration and O2 release was also determined. Rates of CO_2 sequestration were measured both in the liquid and gaseous phases. The researchers found that both methodologies used are adequate for measuring CO_2 sequestration rates in photobioreactors.

Measurements in the gaseous phase detected a maximum CO_2 sequestration rate of 18.7 ± 0.5 mg/L/min and a maximum O_2 release rate of 16.0 ± 0.7 mg/L/min at 96 h of cultivation in the continuous illumination experiment. A strong impact on the gases exchange was observed during cultivations in intermittent light regime, since photosynthetic and heterotrophic metabolisms are occurring in the system. The operation of the system in this condition resulted in a loss of 78% and 65% on the CO_2 sequestration and O_2 release capacity, respectively. It was demonstrated that only a small fraction of the total CO2 sequestered was effectively fixed into the microalgal biomass (3.1 ± 0.05% in average terms). Since the ratio between the CO_2 sequestration and O_2 release rates followed the theoretical photosynthetic value, it was possible to determine that biological sequestration routes were predominant in the photobioreactor rather than physicochemical routes. Possible biological sequestration routes include the excretion of biopolymers and the release of VOCs. These biotransformations of carbon dioxide seem to be the most important sequestration process in microalgal photobioreactors.

The rates of CO_2 capture by algae depends on many factors. Generally, types of photobioreactors, microlgae species and environmental control of important physico-chemical parameters are the main factors influencing the process. Molecular engineering can be used to increase photosynthetic efficiency to enable increased biomass yield. There is also a need to improve temperature tolerance and reduction of photoinhibition that reduces

growth rate. Further efforts on microalgae production should also be focused on reduction costs in cultivating systems and optimization of the microalgae harvesting. Furthermore, developing an efficient oil-extraction method is also a need. The future research should also be focused on developing new technologies or improving existing ones.

7. Removal of air pollutants by plants

It has long been known that plants – mostly trees, shrubs and grasses– can significantly improve the quality of air in urban and rural areas by reduction and/or removal of such pollutants like sulphur dioxide, nitrogen oxides, carbon monoxide and particulates or other pollutants like airborne fluoride. The mechanism of air pollutant removal is mostly dry deposition. The gaseous and particulate pollutants are absorbed by plants through their surfaces. For example nitrogen dioxide and sulphur can be absorbed by plant tissue with carbon dioxide during photosynthesis. Then, the pollutants can be transferred and assimilated by the plant tissue. As for the particulates they can sediment on the plant surface, and then depending on the density and atmospheric conditions (i.e. wind, rainfall, etc.) they can be washed off, suspended again in the air and transported, or they can drop on the ground e.g. with the plant leaves. Due to various conditions (e.g. atmospheric conditions, vegetation) trees can have different abilities for removal air pollutants (Jim & Chen, 2008).

According to the investigations on the removal of air pollutants such as O_3, PM_{10}, NO_2, SO_2, CO by trees on the US urban area, the annual removal was estimated at 711,000 tones (Nowak et al., 2006). Indeed, trees can improve the quality of air by reducing or removing some air pollutants, however it has to be pointed out that some trees can emit biogenic volatile compounds (VOCs) such as monoterpene and isoprene, and in consequence they may have a negative impact on the air quality.

8. Removal of air pollutants in biofilters

Biofiltration is a pollution control method for removal of air pollutants, such as volatile organic compounds and also inorganic compounds (e.g. hydrogen sulfide, ammonia) from airstreams in reactors filled with solid media bed where the pollutants are absorbed/desorbed and oxidized by indigenous microorganisms. The pollutants can be converted to carbon dioxide through microbial activity due to the fact that most odorants present in airstreams from various facilities are biodegradable (Haug, 1993; Deshusses, 1997; Otten et al., 2002).

This method is suitable for treatment of polluted air streams with high volumetric rates and low concentrations of pollutants (Fazaelipoor, 2009). The advantages of biofiltration are: low costs, reliability, public acceptance and environmental friendliness. It can be performed at ambient temperature and does not generate any nitrogen oxides (Deshusses, 1997). However, the efficiency of biofiltration can be affected by excessive loading rates, poor airflow distribution through a biofilter bed, insufficient moisture in a biofilter and uneven distribution of gasses in the treated airstream (Haug, 1993).

Biofiltration occurs through many biological and physicochemical processes and depends on a number of various factors. Therefore in order to obtain high efficiencies of biofiltration the following parameters should be controlled: operating temperature (ambient 15-3540°C or for the maximum degradation rates it should be about 40°C), moisture content (about 60% w.b.), pH (7 to 8,5) air humidity (about 95%), air flow rate (less than 100 m³/h*m²), depth of a biofilter bed (0,5 to 1,5 m high biofilters are used) (Haug, 1993; Otten et al., 2002).

Biofilters were primarily applied to control odors from wastewater treatment plants and composting facilities which emitted off-gasses from biological treatment of wastewater and organic waste. Most recently they are used for other industrial applications. The polluted airstream is humidified and then passed through a reactor column – a packed material with specific microorganisms which are immobilized on the surface of material particles – where the pollutants are degraded by microorganisms present on the surface of solid particle (Haug, 1993; Fazaelipoor, 2009). The types of biofilters can vary significantly. They can be engineered as open or close systems with various media and also multiple beds. Biofiltration media should have high surface area, air and water permeability, water holding capacity, active microbial population and low costs. The materials used for biofiltration include soil, compost, peat, bark, etc. or a mixture of various substrates. They should be biologically active, porous with the void volume about 75-90%, resistant to compaction and contain organic matter (less than 60%) as a source of nutrients (Haug, 1993). Otten et al. investigated compost and perlite mixtures used for biofiltration of butyric acid. The biofilter composed of compost and perlite media showed higher resistance to compaction and higher porosity. The removal efficiency was almost 100%. Pagans et al. (2007) applied compost as a biofilter for simultaneous removal of ammonia and volatile organic compounds emitted from a composting facility. The efficiency of ammonia and VOC removal were about 94,7% and 82%, respectively. Luo & Linsdey (2005) investigated pilot-scale biofilters for odor control at a rendering plant. As a biofiltration media they used crushed pine bark and a mixture of crushed bark and zeolite. The efficiency of odor removal was in the range of 80% to 99%.

9. Conclusion

Living organisms such as microorganisms, plants or animals in their natural habitat have a great potential for the protection of atmospheric air. Since many of living organisms demonstrate bioindication and/or bioaccumulation abilities, they can be employed for biomonitoring of air pollution and removal of various pollutants from the atmosphere. Biomonitoring of air pollution allows for determination of direct biological effects of air pollutants, and therefore it provides an early warning of air quality changes. Moreover, biomonitoring is cost-efficient and as such can be an alternative or complementary tool for analytical methods. Successful biomonitoring approach requires the selection of a suitable biological indicator with a known cause-effect or exposure-response relationship to various air pollutants, designing the observation network and developing a sampling method. In coming years programs for biomonitoring of air pollution will need further development in terms of environmental policies, regulations and methodologies which will assure obtaining statistically reliable data comparable on many levels, such as local, regional or international. Due to the ability to accumulate various air pollutants, many living organisms can be used to reduce the concentration of pollutants in the atmosphere or to mitigate the effects of air

pollution. In recent years, there is an increased interest in biosystems which can integrate the processes for removal of pollutants from atmosphere or industrial airstreams and production of high value products. Such systems can employ algae which are currently being extensively investigated. Industrial airstreams polluted with gaseous substances can be treated in a wide variety of biofilters which demonstrate high removal efficiencies. Plant species such as trees, shrubs or grasses can significantly reduce the exposure to air pollutants, and therefore they should be included in the architecture of urban, suburban and rural areas. As a result of gradual deterioration of air quality and the occurrence of emerging pollutants, many technologies for air protection which employ living organisms will need further development and improvement.

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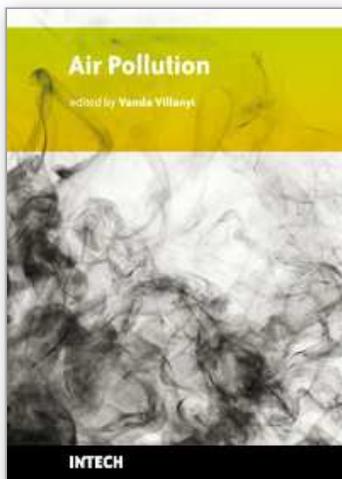
Air Pollution

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Although the climate of the Earth is continually changing from the very beginning, anthropogenic effects, the pollution of the air by combustion and industrial activities make it change so quickly that the adaptation is very difficult for all living organisms. Researcher's role is to make this adaptation easier, to prepare humankind to the new circumstances and challenges, to trace and predict the effects and, if possible, even decrease the harmfulness of these changes. In this book we provide an interdisciplinary collection of new studies and findings on the score of air pollution.

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